

## ANGULAR MOMENTUM PROFILES OF WARM DARK MATTER HALOS

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## ABSTRACT

We compare the specific angular momentum profiles of virialized dark halos in cold dark matter (CDM) and warm dark matter (WDM) models using high-resolution dissipationless simulations. The simulations were initialized using the same set of modes, except on small scales, where the power was suppressed in WDM below the filtering length. Remarkably, WDM as well as CDM halos are well-described by the two-parameter angular momentum profile of Bullock et al. (2001), even though the halo masses are below the filtering scale of the WDM. Although the best-fit shape parameters change quantitatively for individual halos in the two simulations, we find no *systematic* variation in profile shapes as a function of the dark matter type. The scatter in shape parameters is significantly smaller for the WDM halos, suggesting that substructure and/or merging history plays a role producing scatter about the mean angular momentum distribution, but that the average angular momentum profiles of halos originate from larger-scale phenomena or a mechanism associated with the virialization process. The known mismatch between the angular momentum distributions of dark halos and disk galaxies is therefore present in WDM as well as CDM models. Our WDM halos tend to have a less coherent (more misaligned) angular momentum structure and smaller spin parameters than do their CDM counterparts, although we caution that this result is based on a small number of halos.

*Subject headings:* cosmology: theory – galaxies:formation

## 1. INTRODUCTION

Cold Dark Matter (CDM) models of structure formation have been very successful in describing the observed properties of galaxies and their spatial distribution at large and intermediate scales ( $\gtrsim 1 h^{-1}\text{Mpc}$ ). At small ( $\lesssim 100 h^{-1}\text{kpc}$ ) scales, however, there are some uncomfortable discrepancies between the observations and straightforward CDM predictions. One potential problem concerns the sizes and angular momentum content of disk galaxies. Analytic investigations based within the CDM framework have been reasonably successful in reproducing the observed sizes of disk galaxies, but only under the simplistic assumption that disks arise from gas with the same initial average specific angular momentum as their host halos, and that the gas experiences little angular momentum loss during the formation process (e.g., Fall & Efstathiou 1980; Blumenthal et al. 1986; Dalcanton et al. 1997; Mo et al. 1998; van den Bosch 2000; Firmani & Avila-Reese 2000). However, in more detailed numerical galaxy formation simulations, the gas appears to lose a large fraction of its initial angular momentum (e.g., Navarro & White 1994; Navarro & Steinmetz 2000). The resultant disks are considerably smaller than observed disks, unless gas cooling is delayed (Weil et al. 1998) or the efficiency of stellar feedback is enhanced (Thacker & Couchman 2001).

It is not yet clear whether this discrepancy poses a seri-

ous problem for CDM or is simply a result of our insufficient understanding or inadequate numerical modeling of the complicated processes operating during galaxy formation. We can gain some insight into this question by comparing the specific angular momentum ( $j$ ) distribution of dark matter in galactic halos to that of observed for galactic disks. In Bullock et al. (2001; hereafter B01), using a dissipationless CDM plus cosmological constant ( $\Lambda\text{CDM}$ ) simulation, we found that angular momentum profiles of galactic CDM halos of mass  $M_v$  are well described by a two-parameter angular momentum profile of the form

$$M(< j) = M_v \frac{\mu j}{j_0 + j}, \quad \mu > 1. \quad (1)$$

Here,  $j$  is projected along the direction of the total angular momentum in the halo. The parameters  $\mu$  and  $j_0$  fully define the angular momentum content of the halo, where the global spin of the halo<sup>4</sup>  $\lambda' \equiv J/\sqrt{2}M_v V_v R_v$ , is related to  $\mu$  and  $j_0$  via  $j_0 b(\mu) = \sqrt{2}V_v R_v \lambda'$ , where  $V_v$  and  $R_v$  are respectively the virial velocity and virial radius of the halo, and  $J$  is the total angular momentum of the halo. The maximum specific angular momentum in the halo is  $j_{\text{max}} = j_0/(\mu - 1)$ .

This  $M(< j)$  distribution is considerably different from that implied by the mass distributions in disk galaxies (Bullock et al. 2001; van den Bosch et al. 2001; van den Bosch 2001). For example, the dark matter has consider-

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<sup>4</sup> This spin parameter is a practical modification of the conventional spin parameter, defined as  $\lambda = J\sqrt{|E|}/GM_v^{5/2}$ , where  $E$  is the halo internal energy.

ably more low  $j$  material than expected for an exponential disk, and certain models of feedback and bulge formation do not alleviate this problem. It appears, therefore, that in order for CDM to provide a successful theory of galaxy formation, the angular momentum in proto-galactic gas must be rearranged relative to that of the dark matter.

The problem of angular momentum loss and other galactic-scale problems have led some to suggest various modifications to the standard paradigm (Spergel & Steinhardt 2000; Kamionkowski & Liddle 2000). Among the most popular is the recommendation that WDM be substituted for CDM (e.g., Hogan 1999; Hogan & Dalcanton 2000). This acts to suppress power relative to CDM on scales below some filtering scale  $R_f$  related to the WDM particle mass. The formation of halos with masses smaller than the corresponding filtering mass  $M_f$  is thus delayed or completely suppressed. The smaller number of small-mass halos at high redshifts ( $z \gtrsim 3$ ) can help to prevent the excessive transference of angular momentum to the parent halo in cosmological galaxy formation simulations.

Simulations by Sommer-Larsen & Dolgov (2001) indicate that disks formed in the WDM cosmology retain a considerably larger fraction of their angular momentum than their CDM counterparts, alleviating the angular momentum problem discussed above and adding to the motivation for the WDM model. It is interesting therefore to ask whether the specific angular momentum distribution of dark matter in the WDM is also closer to the observed angular momentum distribution of baryons in observed disks. Implications of the WDM scenario have recently been studied extensively using cosmological simulations (Colín et al. 2000; Avila-Reese et al. 2001; Bode et al. 2001; Knebe et al. 2001; Eke et al. 2001). It was shown (Avila-Reese et al. 2001; Bode et al. 2001) that WDM does help to alleviate problems of CDM with halo density profiles and, possibly, spatial distribution of dwarf galaxies (Peebles P.J.E. 2001). In addition, Knebe et al. (2001) compared specific angular momentum distribution in CDM halos to that of the halos formed in WDM cosmology and found no systematic difference. However, they studied halos with masses much higher than the filtering mass of the simulation and neglected the thermal velocities of the WDM particles. The differences in the specific angular momentum distribution are especially pronounced for dwarf galaxies (van den Bosch et al. 2001) and it is therefore interesting to study the angular momentum distribution for halos below the filtering mass.

Additional motivation for this project comes from a desire to understand the nature of angular momentum acquisition in halos, including the origin of the  $j$  distribution. Such an understanding could provide valuable insight into the processes of galaxy formation, e.g., by highlighting specific reasons why (and how) the baryonic  $j$  distribution should differ from that of the dark matter. Traditionally, angular momentum in dark halos has been thought to derive from proto-halo interactions with the large-scale tidal field (Peebles 1969; Doroskevich 1970; White 1984). Recently, however, a scenario in which mergers play a primary role in halo angular momentum acquisition has been investigated (Vitvitska et al. 2001; Maller et al. 2001). Indeed, the real situation may be intermediate to these two pictures. Remarkably, perhaps unfortunately, the shape

of the  $M(< j)$  profile can be reasonably well accounted for using models based in both frameworks. For example, in B01 we presented a model for the origin of profile (1) focusing on angular momentum transfer during minor mergers, as well as a model based on linear tidal torque theory coupled with halo mass accretion histories. Van den Bosch (2001) has explored a similar model, and Maller & Dekel (2001) have investigated a detailed picture for the angular momentum distribution based on multiple satellite accretion events. Formation of such halos in the WDM cosmology should involve very few mergers and one might expect a different resulting distribution of the specific angular momentum if mergers are important in a halo's spin acquisition (Vitvitska et al. 2001; Maller & Dekel 2001).

In this *Letter* we use high-resolution dissipationless simulations of virialized halos formed in the CDM and WDM cosmologies to study the effects of suppressed small-scale power and thermal velocities of DM particles on the halo's specific angular momentum distribution. In particular, we focus on the halos with masses below the filtering mass of the WDM model. The paper is organized as follows. In § 2 we briefly describe the numerical simulations used in our study and present our analysis and results in § 3. Discussion of the results and our conclusions are presented in § 4.

## 2. SIMULATIONS

To study the specific angular momentum distribution of DM halos we used three simulations; one of the  $\Lambda$ CDM cosmology and two of the  $\Lambda$ WDM cosmology. The simulations are described in detail in Avila-Reese et al. (2001); here we will briefly summarize their main features. All simulations were run using the Adaptive Refinement Tree code (Kravtsov et al. 1997; Kravtsov 1999) which achieves high resolution by adaptively refining the initial uniform grid in the regions of interest. The simulations used here were done in a  $60 h^{-1} \text{Mpc}$  box and we focused our analysis on the four most massive halos in this box. The four halos were first selected from a low-resolution  $64^3$  particle run. The particles within two virial radii of the halo centers were traced back to the initial epoch. The initial conditions in the Lagrangian volume marked by the particles were then reset with higher resolution using the multiple-mass technique described in Klypin et al. (2001). The final halos studied consist entirely of the highest resolution particles, of mass  $m_p = 1.1 \times 10^9 h^{-1} M_\odot$ . We used the same power spectrum for both the  $\Lambda$ CDM and  $\Lambda$ WDM runs but in the  $\Lambda$ WDM simulations the modes below the filtering scale,  $R_f$ , were suppressed with an exponential cutoff (Bardeen et al. 1986):

$$P_{\text{WDM}}(k) = P_{\Lambda\text{CDM}}(k) \exp \left\{ -0.5 [kR_f + (kR_f)^2] \right\}, \quad (2)$$

where  $P_{\Lambda\text{CDM}}$  is the power spectrum of the  $\Lambda$ CDM model. The filtering scale defines the characteristic filtering mass  $M_f = 3.65 \times 10^{14} \Omega_{\text{wdm}} R_f^3 h^{-1} M_\odot$  (where  $R_f$  is in  $h^{-1} \text{Mpc}$  and  $\Omega_{\text{wdm}}$  is the warm dark matter density in units of critical density) and is related to the mass of the warm dark matter particle (e.g., Sommer-Larsen & Dolgov 2001; Bode et al. 2001). The warm dark matter particles should also possess “thermal” velocities with an amplitude that is related to their mass. In this study we bracket the possible effects of the thermal velocities by comparing a simulation without thermal velocities

	$\Lambda$ CDM				$\Lambda$ WDM				$\Lambda$ WDM <sub>th</sub>			
Halo	$M_v$	$\mu$	$\lambda'$	$f_m$	$M_v$	$\mu$	$\lambda'$	$f_m$	$M_v$	$\mu$	$\lambda'$	$f_m$
1	9.53	$2.13 \pm 0.55$	0.057	0.02	7.38	$1.19 \pm 0.09$	0.043	0.02	6.61	$1.10 \pm 0.05$	0.035	0.04
2	6.37	$1.22 \pm 0.10$	0.028	0.00	5.73	$1.16 \pm 0.07$	0.041	0.01	14.7	$1.18 \pm 0.09$	0.017	0.14
3	4.44	$1.41 \pm 0.20$	0.023	0.04	3.83	$1.15 \pm 0.05$	0.010	0.27	3.19	$1.10 \pm 0.04$	0.004	0.48
4	5.61	$1.06 \pm 0.02$	0.043	0.16	3.76	$1.23 \pm 0.10$	0.029	0.06	2.65	$1.07 \pm 0.03$	0.023	0.10

Table 1 – Halo properties as obtained in each of the three simulations. For each halo, listed are the values of  $M_v$  in units of  $10^{13} h^{-1} M_\odot$ , angular momentum profile shape parameter  $\mu$ , along with the fit error, spin parameter,  $\lambda'$ , and the fraction of binned halo cell mass that has misaligned (negative) projected angular momentum in the direction of the total halo angular momentum,  $f_m$ .

( $\Lambda$ WDM) and a simulation with thermal velocities sixteen times the value expected for the assumed WDM particle mass,  $m_W = 125$  eV ( $\Lambda$ WDM<sub>th</sub>). The same set of waves was used to set up initial conditions of both the  $\Lambda$ CDM and WDM simulations. Therefore, the same halos form in all the simulations which allows us to compare them individually and gauge the effects of the power spectrum cutoff and thermal velocities more accurately.

### 3. RESULTS

We study four halos in each simulation; each is identified by position, and numbered 1-4. The studied sample of four halos is too small to draw statistical conclusions. However, the identical setup of the initial conditions in CDM and WDM simulations has allowed us to study *systematic* differences between *the same* individual halos formed in two different cosmologies.

Halo angular momentum profiles were constructed using the methods discussed in B01. Briefly, halos were identified using a spherical overdensity method, with the virial radius,  $R_v$ , set using the standard virial overdensity criterion. Once the halo is defined, we use the total angular momentum in each halo to assign the  $z$  direction. We then subdivide the spherical halo volume into many spatial cells, as outlined here using spherical coordinates about the halo center ( $r, \theta, \phi$ ). Radial shells from  $r = 0$  to  $R_v$  are defined such that each contains approximately the same number of particles. The number of shells is always fewer than 30, and we demand at least 500 particles per shell. Each radial shell is then subdivided into three azimuthal cells of equal volume between  $\sin \theta = 0$  and 1, each spanning the full  $2\pi$  range in  $\phi$ . For the halos in this examination, each cell contains between 500 and 1000 particles. The value of  $j$  in the  $z$  direction is measured for each cell and  $M(< j)$  profiles are constructed by counting the cumulative mass in cells with angular momentum less than  $j$ .

Since  $j$  is a projected component, it is possible for a cell to have a negative  $j$  value. Although this is rare (for cells containing  $\sim 1\%$  of the total halo particles, as do ours), it does occur on occasion in CDM halos (B01), and, as discussed below, seems to be more common for WDM halos. When a cell's projected angular momentum is negative, we remove the cell completely from the constructed  $M(< j)$  profile (and do not include the mass in any fits). We record the fraction of halo mass with negative  $j$  and designate it as  $f_m$ . Quoted  $\lambda'$  values do include the particles contained in the negative  $j$  cells, but neglecting them results in changes of less than 5% in  $\lambda'$  in all halos except

$\Lambda$ WDM<sub>th</sub> halo 3.

Table 1 lists the angular momentum properties of all four halos as well as their masses in each of the three simulations. We find that the  $M(< j)$  profiles of every halo are well-fit by the universal curve given by Equation 1. As illustrated in Figure 1, the WDM halos show no systematic difference in their  $j$  distributions compared to the CDM halos, although there is a dramatic decrease in scatter about the average profile.

Note that the masses of the halos systematically decrease as the cosmology shifts from  $\Lambda$ CDM to  $\Lambda$ WDM and again to  $\Lambda$ WDM<sub>th</sub>. The pattern holds for all halos except number 2, which, by chance, has just experienced a major merger in the  $\Lambda$ WDM<sub>th</sub> simulation. The same halo is undergoing a merger in  $\Lambda$ WDM, but the merger has not yet occurred in  $\Lambda$ CDM. A similar trend is apparent in the values of  $\lambda'$ , which decreases systematically from  $\Lambda$ CDM to  $\Lambda$ WDM to  $\Lambda$ WDM<sub>th</sub>. The lone exception is Halo 2 in the  $\Lambda$ CDM simulation, which, because of its lack of a recent merger, may not provide a fair comparison. Similarly, the  $\Lambda$ WDM<sub>th</sub> halos are significantly more misaligned than the  $\Lambda$ CDM halos. Because the thermal velocities in this model are quite high, even at the time of halo turnaround (Avila-Reese et al. 2001), they can influence the measured halo angular momentum greatly. The total bulk rotation at a given halo radius is typically quite small (i.e.  $\lambda' \sim 0.01$ ), so a sizable thermal component can wash out the spin signal, leading to significant misalignment in the measured angular momentum.

### 4. DISCUSSION AND CONCLUSIONS

We found no evidence for a systematic difference in the shapes of the specific angular momentum distributions of WDM and CDM halos. This is a rather puzzling result because there are reasons to expect that the shape of the angular momentum distribution should be sensitive to the merging history of the halos (Vitvitska et al. 2001; Maller et al. 2001). A similar conclusion was reached in a recent study by Knebe et al. (2001). Their conclusion, however, is not very surprising because it applied to halos with masses well above the filtering mass. For halos with masses below the filtering mass, on the other hand, the number of mergers should be greatly suppressed, simply because the abundance of  $M < M_f$  halos is suppressed. Our results thus clearly indicate that minor mergers cannot play a crucial role in shaping the angular momentum distribution. This result poses a challenge for models striving to explain the angular momentum distribution as a result of a series of mergers. Larger-scale phenomena or processes associated

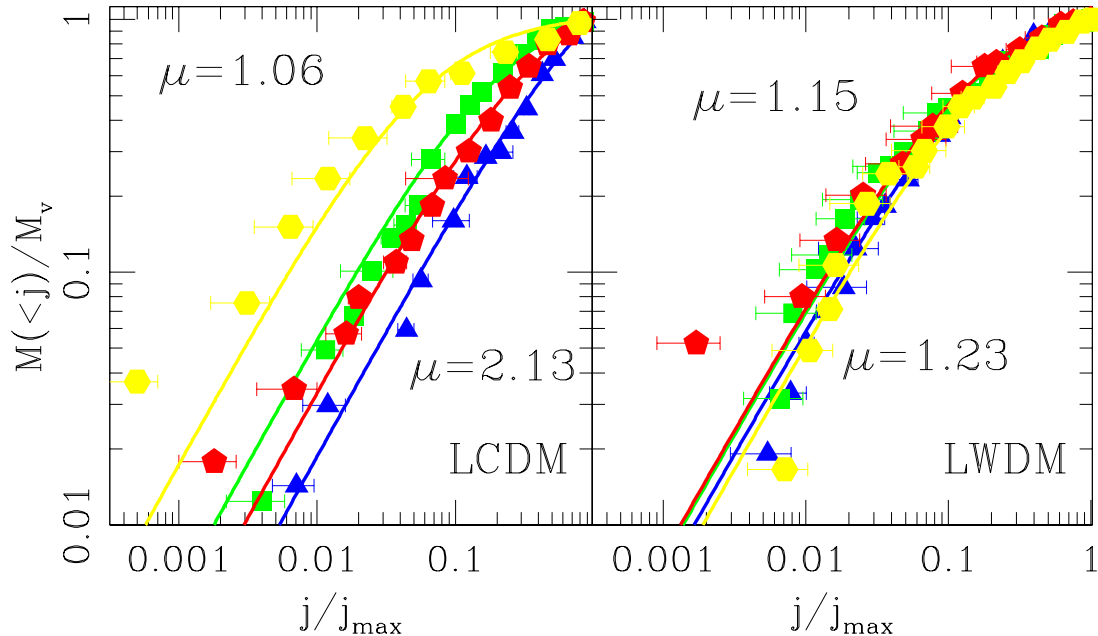


FIG. 1.— Cumulative specific angular momentum distributions for the  $\Lambda$ CDM and  $\Lambda$ WDM halos. Filled points show the profiles as measured in from the simulated halos and solid lines show the best-fit profiles given by Equation 1. Individual halos (identified by matching positions in the two simulations) retain the same point types in both the  $\Lambda$ CDM and  $\Lambda$ WDM panels. Although no systematic differences are observed, the  $\Lambda$ WDM halos demonstrate significantly less scatter about the mean profile.

with halo virialization may be the major contributors.

We found evidence that WDM halos possess systematically smaller spins than their counterparts in the  $\Lambda$ CDM model, although this is based on only three halos. The fourth halo does not follow this trend, however the comparison is somewhat biased because the WDM halo is undergoing a merger<sup>5</sup>. This result is in agreement with findings of Knebe et al. (2001) who reported systematically lower average spins for halos in the WDM models with higher filtering mass using a statistical sample of halos (see their Fig. 15). We showed that the addition of initial thermal velocities of the WDM particles results in even lower spins of the WDM halos as well as a significantly larger misaligned (negative  $j$ ) mass fraction. This is a potentially significant result because previous galaxy formation studies (e.g., Mo et al. 1998) showed that the angular momentum of halos in CDM models is barely sufficient to produce disks with realistic sizes. Although it is not clear why  $M < M_f$  WDM halos should have smaller spins than their CDM counterparts, in the context of merger-driven spin-evolution models (Vitvitska et al. 2001; Maller et al. 2001) it might be expected because they accrete most of their mass quiescently. A decrease in spin during periods of quiescent accretion is also observed in cosmological simulations (Vitvitska et al. 2001).

Recently, Sommer-Larsen & Dolgov (2001) performed gasdynamic simulations of galaxy formation in CDM and WDM models and argued that the WDM model can help to resolve the angular momentum problem. However, this conclusion was true only for simulations in which disk galaxies formed in halos with mass  $> M_f$ , while for halos of mass  $M \lesssim M_f$  they found no increase in the specific

angular momentums of the simulated disks compared to the CDM simulations. If, as Sommer-Larsen & Dolgov (2001) argued, the gas in the WDM model retains more of its initial angular momentum due to the lower abundance of small-mass halos (and hence less efficient cooling of gas at early epochs), this should also be true for the halos with  $M < M_f$ . The relatively small specific angular momentum for the  $M < M_f$  should then be due to the lower overall spin of the gas and DM, which is consistent with the results discussed above.

Unless there is a mechanism which allows baryons to acquire more angular momentum than the dark matter, this result may be problematic for WDM models. Indeed, if, following Sommer-Larsen & Dolgov (2001), one tunes the filtering mass to be  $\sim 10^{10} - 10^{11} M_\odot$  to alleviate the angular momentum problem for massive disk galaxies, the dwarf galaxy disks will then be forming in the lower-spin  $M \ll M_f$  halos. The WDM dwarf disks should, therefore, possess smaller spins than disks formed in comparable mass halos in the CDM models, which are already uncomfortably low compared to the spins of the observed dwarf galaxy disks (van den Bosch et al. 2001). In addition, both the CDM and WDM halos have similarly discrepant  $M(< j)$  profiles compared those of dwarf disks (van den Bosch et al. 2001).

In conclusion, the results presented in this *Letter* show that the change from cold to warm dark matter does not produce the dark matter halos with higher angular momenta or with more desirable specific angular momentum distributions. For WDM disks forming in halos with masses smaller than the filtering mass the angular momentum problem might actually be worse than for the disks

<sup>5</sup> Interestingly, the merger does not drastically affect the shape of the angular momentum profile.

forming in CDM halos of similar mass. Our results therefore fail to provide an additional motivation for the WDM scenario, while highlighting a possibly severe problem at dwarf galaxy scales.

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